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Settlement of a Foundation on a Permanent, Deep Snowpack

George L. Blaisdell and Jason C. Weale

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ABSTRACT

The U.S. Antarctic Program is nearing completion of a nine-year project to reconstruct its primary facility at the South Pole. The new building is elevated and jackable to accommodate bulk and differential settlement into the snowpack. The building's foundation consists of rigidly connected grade beams from which 36 columns extend upward 13 ft (4 m) to support the state-of-the-art living and scientific facility. A limit of 2 in. (50 mm) was established as the maximum allowable elevation difference between adjacent columns to avoid structural damage to the interior of the building. Routine maintenance is required to level and shim columns when settlement limits are near. This report analyzes settlement data for the facility from November 2000 until January 2005. Settlement data so far match the pattern shown in the literature for laboratory tests of static loads on snow. Extrapolation from the most recent 12 months of survey data was used to predict the future elevations of each column for the next several years, leading to recommendations for leveling activities for the coming field season. Predictions of long-term jacking requirements based on the South Pole data match the original design estimates for the theoretical life span of 45 years.

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PREFACE

This report was prepared by George L. Blaisdell, Operations Manager, Office of Polar Programs, National Science Foundation, Arlington, Virginia; and Jason C. Weale, Research Civil Engineer, Applied and Military Engineering Branch, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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GEORGE L. BLAISDELL AND JASON C. WEALE

1 INTRODUCTION

In 1989 the U.S. Antarctic Program began planning for a replacement of its Amundsen-Scott Station, located at the geographic South Pole (Rand and Brier 1999). The existing station, completed in 1975 and near the end of its 20-year design life, was already in critical condition in the areas of safety and ability to support leading-edge research. Equally important, given its location in a region of perpetual snow accumulation, the "on-grade" structure had reached the point of requiring massive amounts of snow removal to keep the station accessible. [The original South Pole station, built on-grade in 1957, is now 30 ft (9 m) below the current snow surface.]

Following considerable debate over the merits of below-, on-, and above-grade construction, it was decided that the most benefit would be derived from a new station built well above grade (Brooks 1999), with the utilities infrastructure (power plant, fuel storage, garage, and shops) below grade in arches. This design is intended to allow air-entrained snow to pass over and under the building, vastly reducing snow drifting (Waechter and Williams 1999). Further, the new Elevated Station is configured to be jackable to facilitate a straightforward service life extension (Berry and Braun 1999).

A multi-year construction project began in 1999—and continues today—to replace the 1975 facility. The old station was designed for an austral summer population of 33 and a winter population of about 12. The new Elevated Station (Fig. 1) is configured in two "C-shaped" pods (each of which contains four wings) to support 150 persons in the 100-day summer season and about 50 in the winter. During construction of the new station, the annual summer population is about 240 so that the construction does not impede the research program for which the U.S. maintains this facility at 90° South latitude. (Extra berthing is

Figure 1. Elevated Station, the centerpiece of the Amundsen-Scott South Pole Station as it appeared on 29 January 2005. The exterior cladding had not yet been applied. The geodesic dome in the background was the centerpiece of the second Amundsen-Scott South Pole Station, constructed in 1975 and slated for disassembly over the next three years. This view is along the 150ºE meridian.

provided by a temporary camp of wooden-platform, canvas-arch modules and newer prefabricated, insulated-panel modules).

Being supported on 36 columns (Fig. 2), the 65,000-ft^2 (6040-m^2), 8.1-million-lb (3.7-million-kg)* building exerts significant concentrated loads on the snow foundation. Considerable thought went into the design of this foundation (Berry and Braun 1999). Of principal concern was settlement, both average and differential, into the deep snowpack present at the South Pole.

Unfortunately for the designers, little practical guidance could be found in the literature. Snow engineering was and remains an immature field, though it has been of keen interest to early polar explorers, to some early-1900s scientists, and to mid-1900s military researchers (Shapiro et. al. 1997). In acknowledgement of these unknowns, the designers elected to construct an elevated snow pad

* In this report, English units will predominate. The English system is used for all survey measurements and construction and maintenance activities at South Pole. Snow densities will only be given in units of g/cm^3 or specific gravity, since this is the standard in snow science; reporting in English units is rare. Multiplying specific gravity by 62.4 lb/ft^3 will yield the unit mass of snow in the English system.

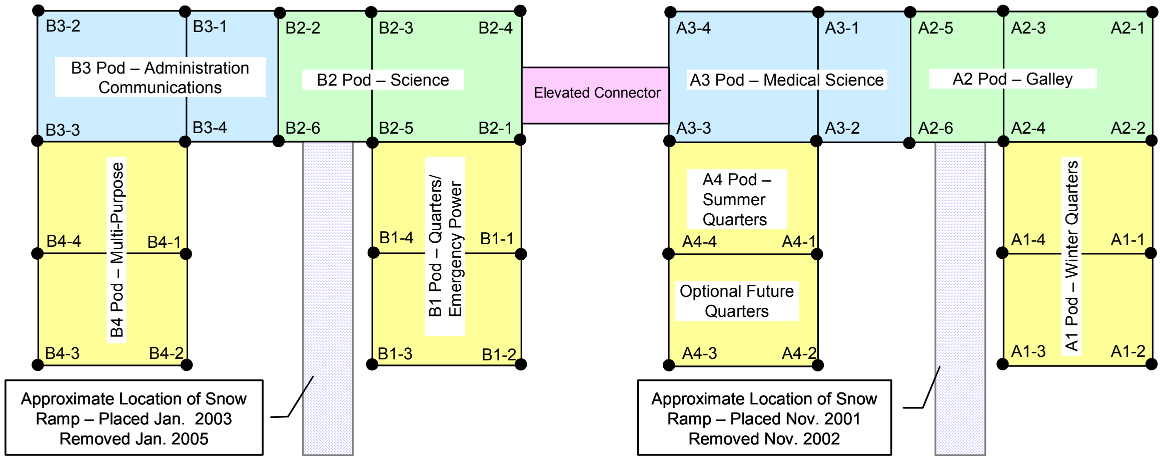

Figure 2. Configuration and nomenclature of wings and support columns of the Elevated Station.

upon which the timber and steel footings of the Elevated Station would be placed. The compacted snow pad, with a size of 150 × 450 ft (45.7 × 137 m) × 6 ft (1.8 m) thick, was constructed to a design density of 0.5 g/cm^3 (33 lb/ft^3) using steel-tracked-tractor compaction of repeated thin (6-in., or 15-cm) lifts of natural snow scavenged from the surroundings. The snow pad exerts a surcharge of 12,600,000 lb (5,715,000 kg) on the existing snow surface. The snow underlying the pad exhibits a significant difference in properties because part of the area had been a taxiway and parking location for aircraft. The goal of the snow pad was to:

- Assist in the uniform and predictable spreading of concentrated footing loads;
- Mitigate non-uniform snow properties that exist normally (and in this case were known to vary from past activity) in the natural snowpack; and
- Raise the station above the local surface elevation.

The nature of the construction sequence of the Elevated Station and performance monitoring during construction has progressed in a sub-optimal manner from the standpoint of an engineering experiment. Nonetheless, several years of valuable data are now available, even with the continuation of the construction process. The exercise described here is aimed at:

- Determining the settlement rate of the station's support columns as a function of time since loading;
- Determining the degree and dynamic nature, if any, of differential settlement;

- Determining the potential for using data collected so far to develop an analytical model for foundations at South Pole suitable for use in managing and planning maintenance associated with the building: and
- Establishing a knowledge base applicable to future planned large infrastructure on deep snow foundations.

This report was developed to provide NSF with guidance regarding planning for column jacking procedures (if required) for the 2005–2006 and 2006–2007 field seasons. We recognize that additional survey data have become available between the development of the recommendations and the publishing of this report. Those data are continuously being added to our database and we are re-evaluating our predictions. We hope to publish an addendum that includes all available survey data once the station construction is complete.

2 BASIC SITE CHARACTERISTICS

The natural snow surface at the geographic South Pole has an elevation of 9,295 ft (2,833 m). Bedrock at this location is essentially at sea level. Little "fresh" snow falls at South Pole. Snow does enter the area (and leaves) via wind-borne transport from the vast surrounding polar plateau. With a mean annual temperature of –56°F (–49°C), no melting occurs. A net flux difference accounts for a snow accumulation rate in the region of South Pole (away from any human influence) of 8 in. (20 cm) per year (Mosley-Thompson et al. 1995).

The massive thickness of snow consolidates under the influence of gravity, resulting in a vertical density gradient from snow at 0.35 g/cm^3 (35% ice; 65% air and water vapor) at the surface, to firn at 0.55 g/cm^3 at 25 ft (7.5 m) deep, to glacial ice of greater than 0.92 g/cm^3 below about 375 ft (115 m). Additionally, being a super-cooled liquid, the ice sheet at South Pole is influenced by topographic gradients at its base and surface. "Downhill" for the ice at South Pole is south along the 143°E meridian, continuing north after reaching the geographic pole along the 37°W meridian. Movement is at a rate of 33 ft (10 m) per year.

3 SURVEY TECHNIQUES AND BENCHMARK

In January 1974 the Naval Civil Engineering Laboratory (NCEL), a major contributor to the design and construction of the existing station, established a “stable” benchmark (BM). This BM is located inside the geodesic dome (Fig. 1) that contains the major facilities of the 1975 station and is thus protected. From field notes taken at the time of installation,* the BM was described as “a deep snow bench mark” and “is located adjacent to the stairwell on the grid south end of the Science and Operations building. A SIPRE auger was used to drill a 30-ft- (9.1-m-) deep hole, and a 3.5-inch- (89-mm-) diameter aluminum pipe was used to case the hole. A 40-ft (12.2-m) section of 1-inch- (25-mm-) diameter pipe was placed in the hole. The 1-inch (25-mm) pipe was driven the last 10 ft (3.1 m) with a hammer and then 1 gallon (3.8 liters) of water was dumped down the hole to freeze in the pipe.” This NCEL BM has been used as the reference for all surveys at South Pole since its establishment. The BM is obviously moving with the rest of the terrain at the South Pole, but the top of the BM is considered the reference point for all spatial measurements, so a Lagrangian frame of reference (Malvern 1969) exists at South Pole.

All of the survey data for the new Elevated Station have been collected using conventional “rod and level” surveying techniques (Fig. 3). Because the NCEL BM is located in the snow floor of the old station, several “turning points” are required to move to a position where elevations can be collected for the Elevated Station. To reduce the time to complete a survey, an intermediate BM is frequently used as the origin. This BM is the top of a metal bollard located immediately adjacent to the entrance to the vehicle maintenance garage and requires only two “turns” before surveyors collect Elevated Station survey data. Periodically, the elevation of this station is re-established by reference back to the NCEL BM.

* Personal communication with F. Brier, 2002.

Figure 3. Workers collecting column elevations as part of a monthly survey during the austral summer field season. Note the welded tab protruding from the top of each column, from which the survey measures column elevations.

4 SETTLEMENT

Survey data are collected for the Elevated Station columns at monthly intervals during the South Pole summer season (mid-November to mid-February). Attempts have been made to make exterior survey measurements at least occasionally during the austral winter, but climatic conditions have made this impossible so far.

Elevations are taken at a welded tab near the top of each support column on the station (Fig. 3). Since construction of the station has necessarily been sequential, some columns have been in place longer and thus have a longer elevation history. Generally, initial survey data are taken for individual wings of the station when all of that particular wing's support structure (timbers, grade beams, and columns) are complete.

Because of the dynamic terrain, we assumed that the only time a group of columns was truly level at its top loading point was at the initial survey event, that is, at the completion of construction of a wing or group of wings. Any differences in elevation relative to the long-established, but moving, NCEL benchmark at this survey event were assumed to be within the local construction and survey accuracy limits. Unfortunately, these survey data were usually collected at the end of the summer season, meaning that nearly nine months ensued before the next set of elevation data became available.

Settlement data for all of the Elevated Station columns currently in place, and with at least two survey data sets available, are shown in Figure 4. The abscissa on the graph is time since the first survey of the first set of columns (Wings A1 and A2), which occurred on 15 November 2000. The foundation for these columns was prepared between 10 and 14 February 2000, and the columns themselves were placed between November 2000 and February 2001 (Fig. 5). The ordinate of the graph is penetration (settlement), by column, relative to the first recorded elevation *of that column*. The first recorded elevation of any column, no matter what its actual height above the control benchmark, is plotted at zero. All elevations subsequently measured for that column are compared to its initial elevation, and the difference is the value shown in Figure 4.

The first impression from these data is that the station is settling at a reasonably linear and uniform rate. Comparing these settlement curves with those found in the literature shows several differences. The accepted shape of a snow settlement/creep curve is more strongly logarithmic (Wuori 1957) (Fig. 6), compared to the very gentle curve seen in our data (Fig. 4). This may be due to the low frequency of survey data collected in the early life of each of the Elevated Station's

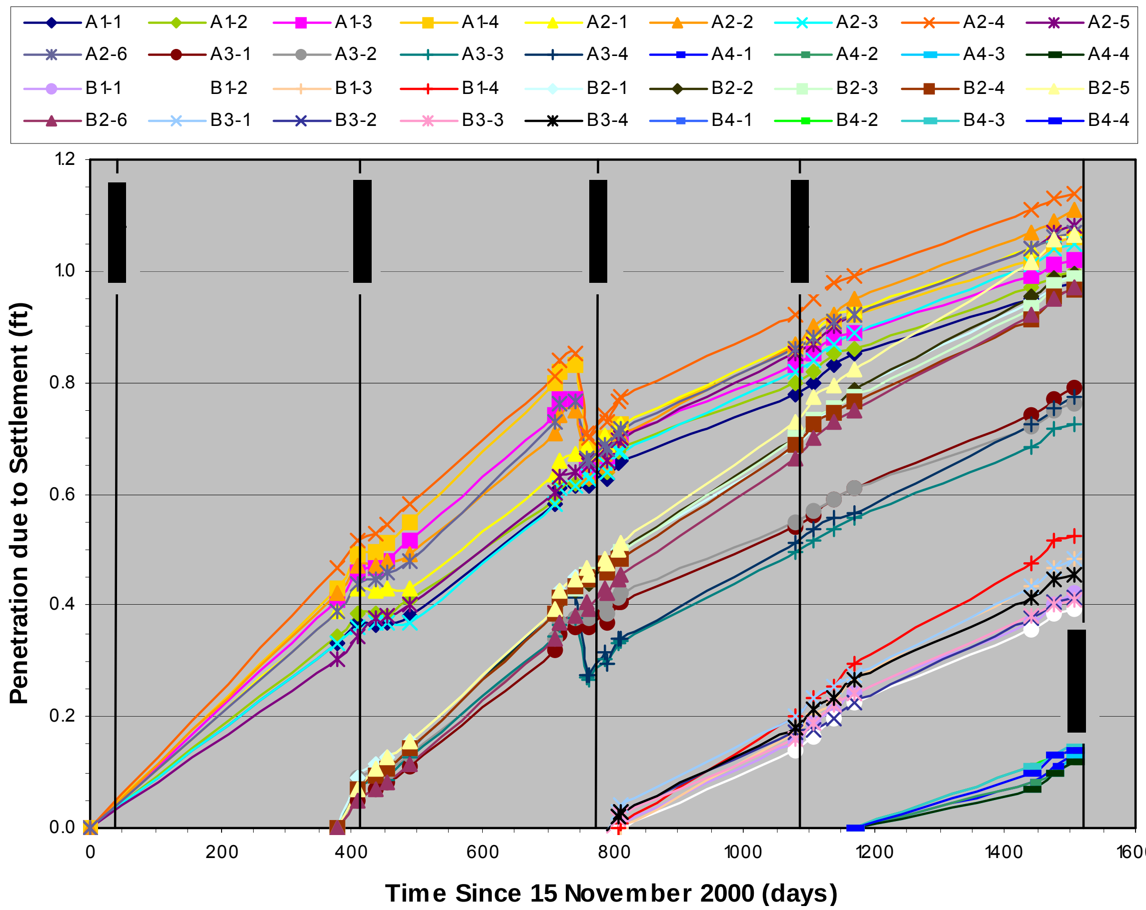

Figure 4. History of column settlement for the Elevated Station. The lifting and shimming of some columns in December 2002 can be seen clearly by the sudden changes in several traces. (See also Fig. 18–20 for plots of individual station wings.)

column. Even if monthly data were available, this may be too infrequent to capture the initial "settling in" of the foundation as the timber footers and grade beams distribute localized stress concentrations over a broader portion of the bearing surface.

Additionally, published settlement results (Wuori 1957) usually show a very quick transition to a horizontal asymptote. Some tests show transitions on the order of minutes or days before settlement is reduced to very small levels with each successive unit of time. This disparity may reflect the fact that most data displayed in the literature derive from tests where a full-load condition is placed on a footing instantaneously. The Elevated Station columns often remain with only a partial load (e.g., self-weight) for as much as a year before being gradually loaded as the exterior and interior construction takes place over ensuing years

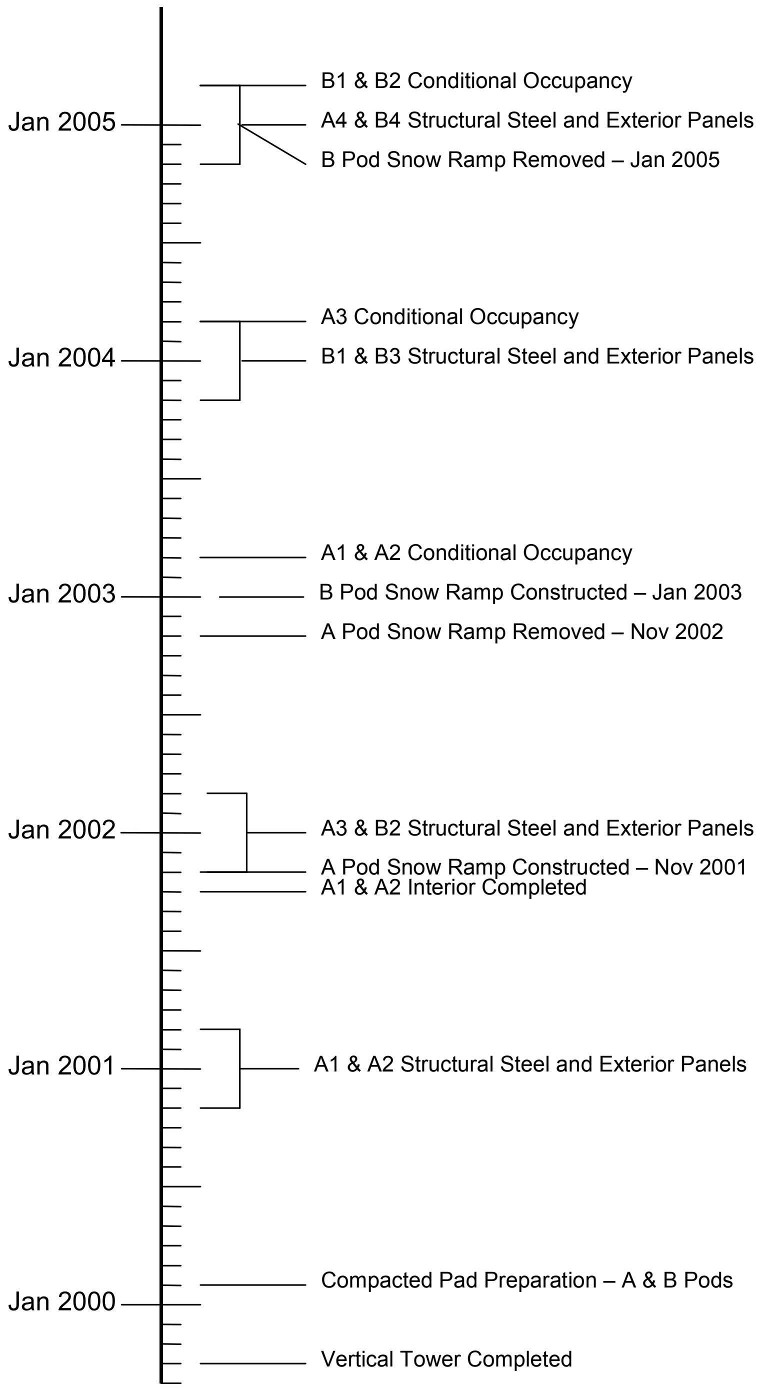

Figure 5. Timeline of major construction milestones for the Elevated Station.

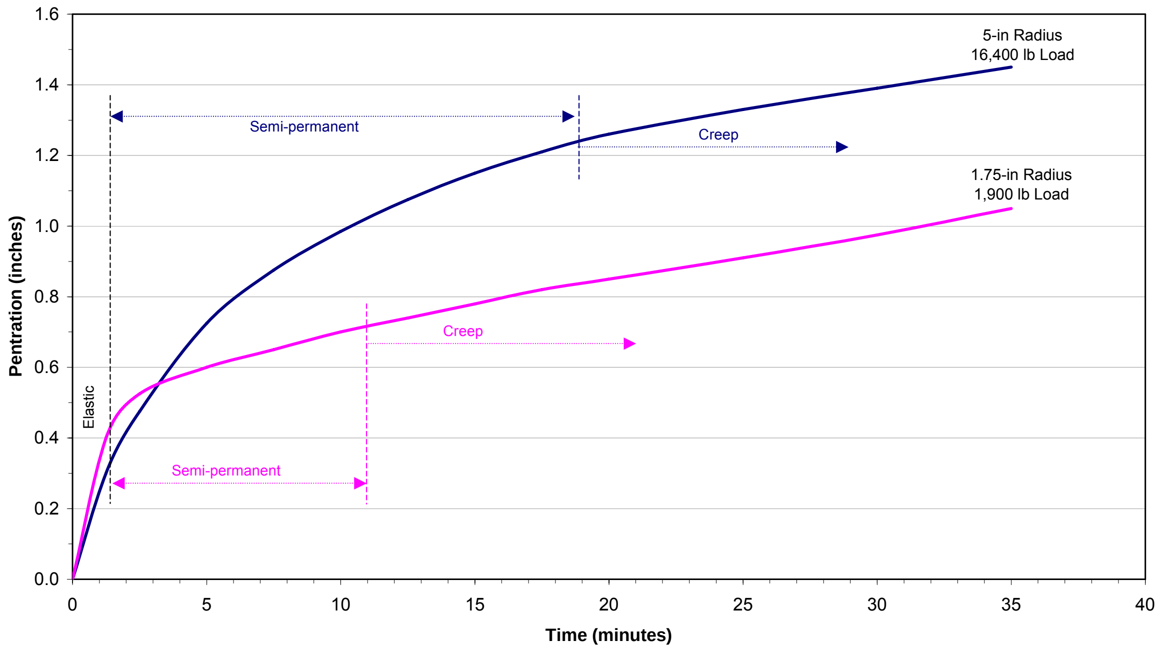

Figure 6. Penetration of circular bearing plates under a constant load as a function of time. The snow temperature is –9°C, the density is 0.53 g/cm^3, and the age is 8–10 days. (After Wuori 1957.)

and eventually the live load is introduced. A number of columns still do not carry their full intended dead load, and currently only Wings A1, A2, and A3 have the majority of their live loading.

Because of the excess differential settlement as shown in Figure 4 (illustrated by diverging traces), in December 2002, seven columns were re-leveled (A1-3, A1-4, A2-2, A2-4, A2-6, A3-3, and A3-4). Shims were added beneath the grade beams (which rigidly connect the columns in a grid pattern) in these locations to bring into better harmony the level of these particular wings. The structural criteria established in the basis-of-design of the Elevated Station limits the differential settlement between “adjacent support points” to 2 in. (50 mm) (Berry and Braun 1999). Berry and Braun further state that if the 2-in. (50-mm) limit is exceeded, “the superstructure will be leveled.” If taken literally, this implies that, when it was noted in December 2002 that some of the columns had or would soon exceed their differential settlement limits, all of the columns of the station would be adjusted to re-establish the tops of the columns at a uniform level horizon (resulting in the building floor being level). This was not done; however, the lifting and shimming of selected individual columns did bring the outliers into a better degree of levelness with the other columns within a wing, as can be seen clearly in Figure 4.

Table 1. Wing settlement rates by year (in. per year).

Wing	Average for History	Nov 2000–Nov 2001	Change 2001 to 2002	Nov 2001–Nov 2002	Change 2002 to 2003	Nov 2002–Nov 2003	Change 2003–2004	Nov 2003–Nov 2004
A1	2.9	4.4	–0.4	4.0	–1.8	2.2	–0.4	1.8
A2	2.9	4.5	–0.5	4.0	–1.4	2.6	–0.4	2.1
A3	2.8			4.4	–1.9	2.5	–0.2	2.3
A4	1.5							1.3
B1	2.9					2.8	0.0	2.8
B2	3.8			4.9	–1.3	3.6	–0.7	2.9
B3	2.7					2.7	–0.1	2.6
B4	1.9							1.9

The historical survey data show that the settlement rate of a particular column remains remarkably consistent relative to other columns in its group before and after lifting and shimming. We found this notable in that it could be assumed that the load-sharing feature of the grade beams would cause a significant and instantaneous shift in local settlement rates when a column base moved from being at one of the lowest horizons to being one of the highest horizons within a wing. This apparently does not happen. In fact, even diverging settlement rates for pairs of columns within Wing A3 can be seen to be preserved before and after adjustment (A3-1/A3-2 compared to A3-3/A3-4).

Recognizing that some initial curvature in the traces in Figure 4 is probably missing, and that our data frequency is essentially once per year, we first applied a linear regression analysis. This was performed over the span of individual years for each wing (Table 1) and shows clearly (and fortunately!) that sinkage of the Elevated Station is slowing. This suggests that, in time, the Elevated Station will demonstrate classic snow settlement behavior.

It is curious to see that the changes in settlement rate for individual wings are not consistent over time, both speeding up and slowing down (Fig. 7). This is an interesting result, given that (a) the wings are at different stages of their career, (b) there are significant differences in the gross load on each column (despite having a nearly uniform contact pressure because of the variable-width footers), (c) the loading on columns and grade beams has been increasing over the period of this analysis, and (d) the timber footers under the columns and grade beams are designed for the final loading level (which in a number of cases is quite different from the current load). While following a pattern of change similar to the

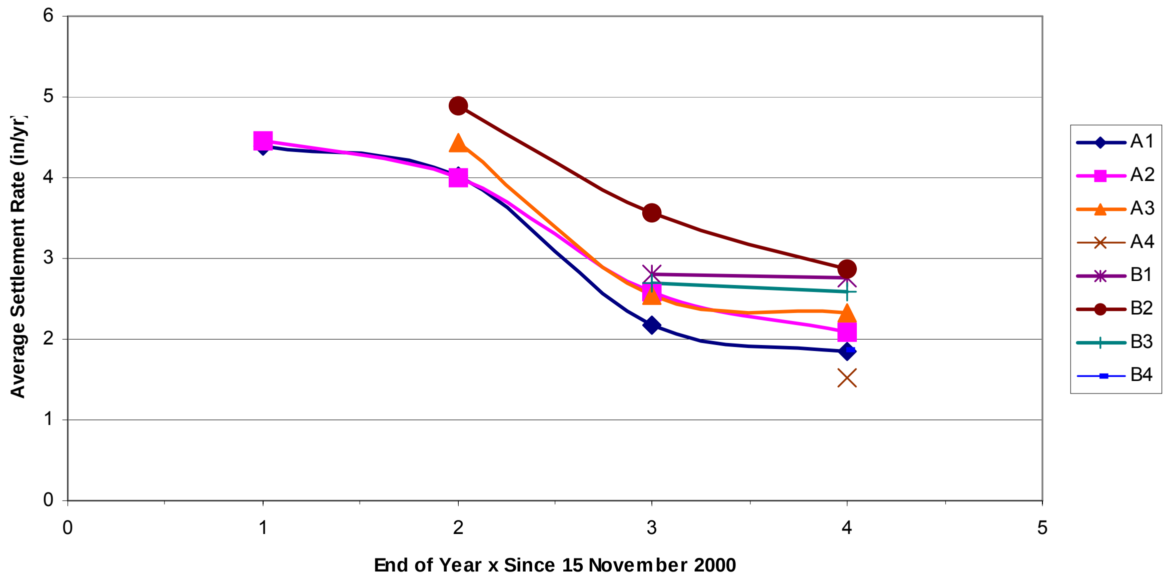

Figure 7. History of change in rates of settlement of individual wings of the Elevated Station.

other wings, until November 2004, Wing B2 had demonstrated a persistently higher rate of settlement; it now appears to be joining the range of rates spanned by the other wings.

Viewing all the settlement rate data together shows a remarkable consistency in behavior as a function of time, regardless of how long it has been since a wing was constructed (Fig. 7). This is most clearly seen with the second group of wings constructed (A3 and B2), which show a large change in settlement rate during their *first* year of existence. This coincides by date (November 2002 to November 2003) with a similar change in rate within the A1 and A2 Wings, during their *second* year of life. The B1 and B3 Wings also show very little change in settlement rate during their *first* year after construction, as the A1 and A2 Wings had two years prior but unlike Wings A3 and B2.

The strong link between variations in settlement rate change and calendar date suggests a global influence. We suspect this may be settlement associated with the snow pad that supports the entire station. However, why there would be such dramatic changes in settlement rate (both speeding up and slowing down) for the dense snow pad into the "natural" snow on which it was built, at this point in its life, is not obvious.

There is clearly differential settlement among the columns, even within a particular wing (Fig. 4). However, following the first year after installation, differential settlement does not seem to be increasing but remains fairly uniform, as seen by the small and linear divergence of the settlement traces.

An odd feature of Figure 4 is the irregular nature of settlement during the South Pole summer (mid-November to mid-February), when measurements are taken at least monthly. Very few of the column's data depict a smooth settlement pattern over these four or five closely spaced measurements. We initially suspected that this indicated difficulties for the surveyor(s) in completing a close-tolerance survey under the South Pole conditions. While this may well be a contributing factor, several different surveyors, representing a range of experience levels including a veteran Antarctic surveyor, have executed the measurements (including two independent corroborating surveys within a few days of each other), suggesting there are likely other, physical, reasons.

Perhaps this is associated with the load sharing that occurs among columns because of the rigid connections to the grade beams in response to differences in settlement. This would be in keeping with the design (Berry and Braun 1999), where "the grade beams … act similar to a raft foundation system because it has the stiffness to distribute vertical loads along the grade beam if one area settles more than an adjacent area. This bridging ability to straddle soft areas … increases the bearing pressure on stiffer areas, and gives the foundation self-leveling capabilities to limit differential settlement." In this process, it is conceivable that, after some limited period of time, one or more columns nearby may feel enough increase in load to cause an acceleration in their local settlement rate until the load begins to transfer in the opposite direction. Viewed over all the columns, this may appear as if there is a random pulsing of settlement behavior.

This explanation may appear to disagree with our earlier observation that shimming apparently did not change the overall rates of settlement. That observation was drawn from looking at long-term trends (12 months and more), while the behavior postulated here is seen at a monthly frequency. The short-term pulsing behavior may be persistently superimposed on the long-term rate trend and may only be obvious when data are collected frequently.

Another possibility is that the pulsing is associated with construction activities and represents the foundation's response to widely and rapidly changing loads when unfinished wings are used for temporary but concentrated staging of construction materials, and as elements of the station are completed and begin to assume their live load over the course of as little as 100 days.

For the A1, A2, A3, and B2 Wings, an adequate survey history is present, and evidence of slowing settlement rates, to attempt non-linear curve fitting (Fig. 7). We used a second-order polynomial for these data sets and obtained excellent correlation (r^2 >0.95). However, this curve, when extrapolated into the future, quickly and dramatically departs from realistic settlement (predicting too little settlement). It might, though, be a simple and reasonable tool for short-term

extrapolation (one year). Only two years have passed since the B1 and B3 Wings were first surveyed, and only a single year of data is available for the remaining columns (Wings A4 and B4). This is inadequate for non-linear curve fitting, so only a straight-line fit could be determined for these data sets. Unlike the polynomial used for the A1, A2, A3, and B2 Wings, however, this will likely yield a conservative (too large) prediction of future settlement.

5 EFFECT OF SNOW RAMPS

The exterior shell of the Elevated Station was constructed using cranes, as is typical with any structure having significant height. With the bottom of the building elevated some 20 ft (6.5 m) above the surface, it was necessary to make provisions to lift materials destined for the interior up to at least the first-floor level. We understand that construction plans called for this to be done with high-lift loaders or other material-handling equipment and an interior freight elevator.

In reality, a snow ramp was constructed to allow conventional and existing loaders and transport equipment to reach the level of the loading docks on the first floor (Fig. 8). This certainly increased the flexibility for materials handling for the construction teams at South Pole, especially during the austral winter, when high-lift equipment hydraulics tended to balk.

The first snow ramp was constructed for the A Wings in November 2000 and remained in place for 12 months. This ramp was at the downwind end of Wing

Figure 8. Snow ramp adjacent to the Wing B1 allowing direct delivery access to the loading dock on the back (downwind) of the B2 Wing. This photo was taken 7 November 2004, prior to completion of Wings A4 and B4 superstructure. The view is along the 45ºE meridian.

A1, and the entrance was through a modified personnel door. In November 2001 a second snow ramp was constructed that abutted the Wing A2 cargo deck. This ramp was roughly 25 ft (8.2 m) wide at its base, 140 ft (46.5 m) long, and 20 ft (6.5 m) tall at the point where it abutted the A2 Wing. At a snow density of 0.5 g/cm^3, the ramp's mass was greater than 1,000,000 lb (450,000 kg). At the tall end, the ground pressure exerted by the ramp at the level of the Elevated Station's grade beams was 625 lb/in^2 (44 kg/cm^2), or nearly 100 times the design footprint pressure for the timbers transferring the column and grade beam loads to the snow. Being in such close proximity to columns A1-3, A1-4, A2-4, and A2-6, it could be expected that they might suffer greater settlement rates than columns farther from the ramp. Indeed, all four of these columns were among the seven that required lifting and shimming in December 2002. The data also show clearly that columns A1-4 and A2-4, being closest to the greatest surcharge, showed the fastest settlement rates during the period of ramp residence.

The second snow ramp was removed in January 2004. However, Figure 4 shows that the settlement rate for at least column A2-4, the most heavily loaded, did not immediately slow down. The data suggest that at least until the last survey of the austral summer season (4 February 2004), this column showed faster sinkage than others in the A-Pod. Since then, though, the columns in Wing A2 show a very similar settlement rate, with column A2-4 showing a persistent but constant offset.

A similar snow ramp (Fig. 8) was built for the B-Pod construction effort in January 2004 and removed in January 2005. It would seem reasonable to expect that columns B1-3 and B1-4, and especially B2-5 and B2-6, would show accelerated settlement rates compared to the remainder of the B-Pod columns. This is borne out by data collected over the past year; clearly column B2-5 is settling at a rapid rate (Fig. 4). Columns B1-3 and B1-4 also show an accelerated sinkage rate compared to the remaining B-Pod columns. Surprisingly, column B2-6 does not show an increased rate.

In January 2005, column B2-5 was lifted 1.25 in. (32 mm) and shimmed at its top. It is too soon to tell what the new rate of settlement will be for the columns affected by the snow ramp. Thus, until the 2005–2006 austral summer season when new data will become available, we will assume that the current settlement rate continues to apply, understanding that it will most likely lead to conservative predictions of future column heights.

A fourth ramp was built in January 2005 to gain access to the downwind end of Wing B4; it is slightly smaller than the prior ramps but was constructed in a similar fashion.

6 PREDICTION OF LEVELING INTERVAL

To adhere to the Elevated Station design parameters (less than 2 in., or 50 mm, of differential settlement between adjacent support points), it is necessary to anticipate at least a year in advance when this limit will be reached to allow proper planning for the equipment, labor, and materials needed to carry out lifting and shimming. Considering it the most accurate but yet conservative prediction method, we linearly extrapolated the settlement data for the last year of data collected for each column. This takes into account only the most recent behavior of each column and assumes no major slowing in settlement rate, leading to at most a slightly exaggerated estimate of settlement.

Table 2 gives the settlement rate for the period 30 December 2003 to 31 December 2004 for each column. Recognizing that each column top is currently at a slightly different elevation (i.e., the base of the building on 31 December 2004, the date of the last survey used in this analysis, is not level; Fig. 9), we predicted elevations for each column at the beginning of each of the next three years (Table 2). Comparing column elevations at yearly intervals into the future allowed us to estimate the offset of adjacent columns to test against the design limits (Fig. 10–12).

A similar exercise performed shortly prior to the beginning of the 2004–2005 field season led to the lifting and shimming that occurred in January 2005 for column B2-5. This action mitigated excessive differential elevations that were predicted to be reached prior to the onset of the next austral summer season.

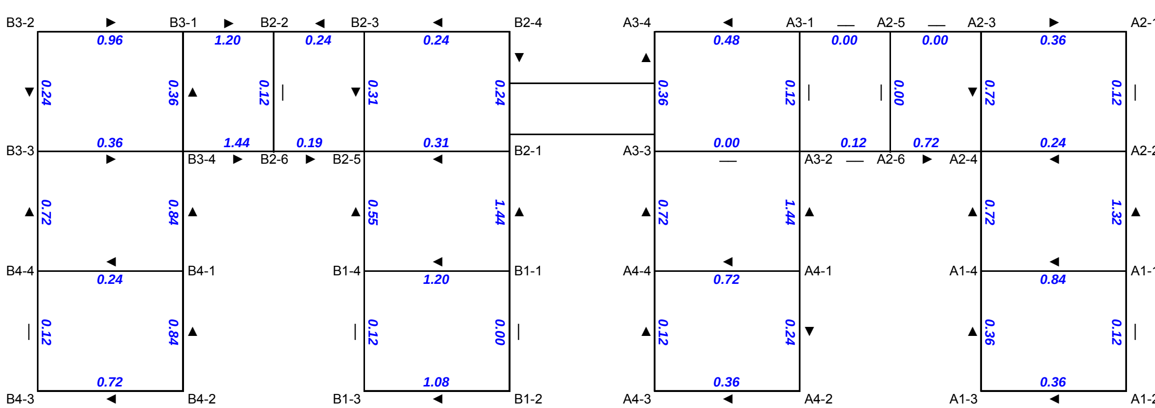

Figure 9. Elevation differences (in inches) between adjacent support columns of the Elevated Station based on survey data collected on 31 December 2004. (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level.)

Table 2. Measured elevation of columns on 1 January 2005 and prediction of future column elevations based on extrapolation of settlement rate (linear) from the latest year of survey data. (The reference for the survey is the NCEL benchmark.)

Column	Most recent settlement rate (in./yr)	Elevation (ft)			
		1 Jan 05	1 Jan 06	1 Jan 07	1 Jan 08
A1-1	1.75	44.21	44.06	43.92	43.77
A1-2	1.81	44.20	44.05	43.90	43.75
A1-3	1.68	44.17	44.03	43.89	43.75
A1-4	1.78	44.14	43.99	43.84	43.70
A2-1	1.81	44.11	43.96	43.81	43.66
A2-2	2.15	44.10	43.92	43.74	43.56
A2-3	2.12	44.14	43.96	43.79	43.61
A2-4	1.95	44.08	43.92	43.76	43.59
A2-5	2.12	44.14	43.96	43.79	43.61
A2-6	1.95	44.14	43.98	43.82	43.65
A3-1	2.31	44.14	43.95	43.75	43.56
A3-2	1.99	44.13	43.96	43.80	43.63
A3-3	2.26	44.13	43.94	43.75	43.57
A3-4	2.64	44.10	43.88	43.66	43.44
A4-1	1.60	44.25	44.12	43.98	43.85
A4-2	1.48	44.23	44.11	43.98	43.86
A4-3	1.52	44.20	44.07	43.95	43.82
A4-4	1.46	44.19	44.07	43.95	43.83
B1-1	2.79	44.27	44.04	43.81	43.57
B1-2	2.87	44.27	44.03	43.79	43.55
B1-3	2.76	44.18	43.95	43.72	43.49
B1-4	2.63	44.17	43.95	43.73	43.51
B2-1	3.24	44.15	43.88	43.61	43.34
B2-2	2.85	44.13	43.89	43.66	43.42
B2-3	2.72	44.15	43.92	43.70	43.47
B2-4	2.60	44.17	43.95	43.74	43.52
B2-5*	2.29	44.12	43.93	43.74	43.55
B2-6	2.60	44.14	43.92	43.71	43.49
B3-1	2.38	44.23	44.03	43.83	43.63
B3-2	2.33	44.31	44.12	43.92	43.73
B3-3	3.00	44.29	44.04	43.79	43.54
B3-4	3.17	44.26	44.00	43.73	43.47
B4-1	1.90	44.33	44.17	44.01	43.85
B4-2	1.84	44.40	44.25	44.09	43.94
B4-3	1.90	44.34	44.18	44.02	43.86
B4-4	1.81	44.35	44.20	44.05	43.90

*Includes 1.25-inch lifting/shimming in January 2005.

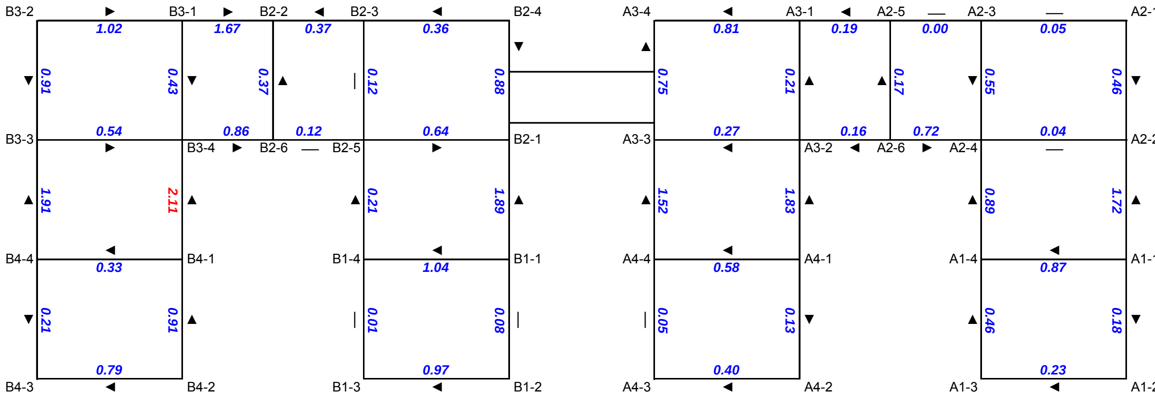

Figure 10. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2006. (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level. Values in red indicate column pairs that exceed design limits for differential elevation.)

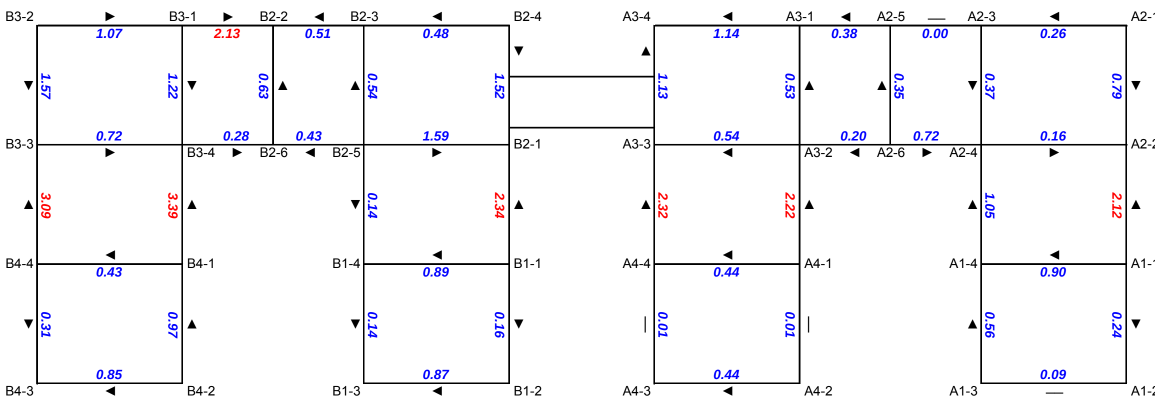

Figure 11. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2007. (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level. Values in red indicate column pairs that exceed design limits for differential elevation.)

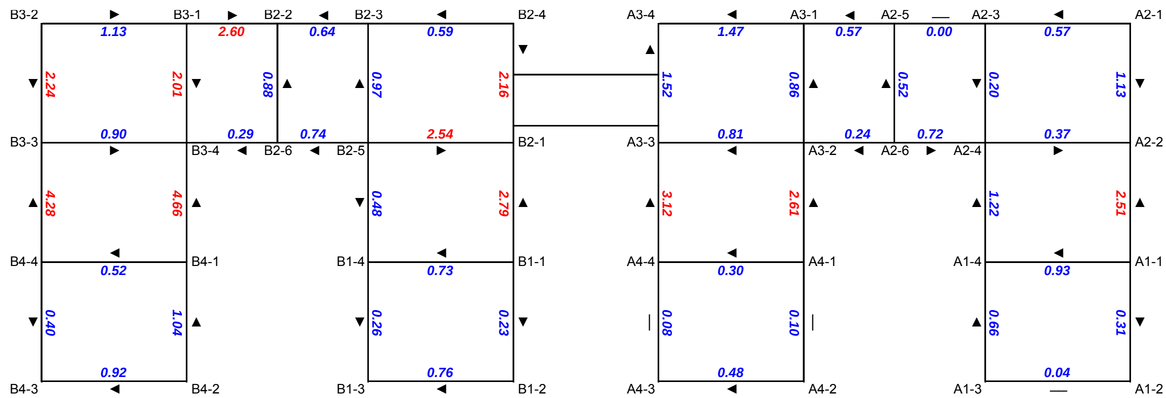

Figure 12. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2008. (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level. Values in red indicate column pairs that exceed design limits for differential elevation.)

The more thorough analysis described here predicts that columns B3-4 and B4-1 will differ in elevation by more than 2 in. (50 mm) by the beginning of 2006 (Fig. 10). Further, we predict that six other adjacent column pairs will exceed 1.5 in. (38 mm) by the middle of next field season. Of note is that six of these seven column pairs have an identical orientation and fall along a single row of grade beams. Significantly, they all have the same pitch direction, downhill toward the front of the Elevated Station (Fig. 10). These six pairs represent all but two of the connectors between the east–west-trending front of the station and the north–south, downwind segments of the structure. The two connectors not on the list, A2-4/A1-4 and B2-5/B1-4, have already required lifting and shimming (December 2002 and January 2005, respectively).

This aspect of station settlement seems particularly important. It may suggest that there is an inherent lack of structural stiffness between the front and "tails" portion of the station. It may also be linked to a construction flaw in the preparation of the snow pad under the foundation, but it seems unlikely that such a flaw would be so extensive and linearly defined. While the two massive snow ramps existed in the interior of each of the Elevated Station's "C-shaped" sections, they were located very close to the A1 and B1 Wings and thus were quite distant from some of the grade beams (e.g., connectors A3-3/A4-4 and B3-3/B4-4). Therefore, we think it unlikely that the ramps can explain this distinct pattern of differential settlement.

The prediction for January 2007 (Fig. 11) is used to plan the lifting and shimming required during the upcoming (2005–2006) field season. It suggests that seven pairs will require attention. Given the materials, equipment, and

expertise required to perform this leveling, it may be efficient to shim column pairs B2-1/B2-5, B2-1/B2-4, and B3-2/B3-3 at the same time. (The probable slowed settlement rate of column B2-5 may avoid the need to consider adjusting the first pair in this list, but it is not likely to alter the other pairs significantly enough to reduce substantially the overall effort required during the 2005–2006 field season.)

Were lifting and shimming to be postponed, the prediction for January 2008 (Fig. 12) dictates that during the 2006–2007 field season, 11 column pairs would exceed the design limits and would require leveling. By that time (January 2007), our predictions indicate that the largest elevation difference would be 4.7 in. (119 mm) between columns B3-4 and B4-1.

We strongly recommend that shimming be performed in the 2005–2006 field season. Certainly, new survey data will result in annual revision of the settlement rates for each column. An analysis such as presented here should be completed annually, resulting perhaps in a change in recommended shimming. However, at this time, we are confident in making the following recommendation.

Working to minimize the effort required, but to gain the maximum longevity, we recommend that six columns be lifted as shown in Table 3. Our recommendation results in there being one column pair (B3-1/B3-4) at just over 2 in. (50 mm) immediately following shimming (Fig. 13) but avoids any shimming needed in the 2006–2007 season (Fig. 14). By the 2007–2008 season, one column pair (B3-4/B4-1) will be slightly past the differential design limit (Fig. 15).

Table 3. Recommended lifting and shimming to be performed between December 2005 and January 2006.

Column	Elevation change (in.)
A2-2	+1.50
A4-1	–1.25
A4-4	–1.50
B2-1	+1.50
B2-2	+2.00
B2-6	+2.00

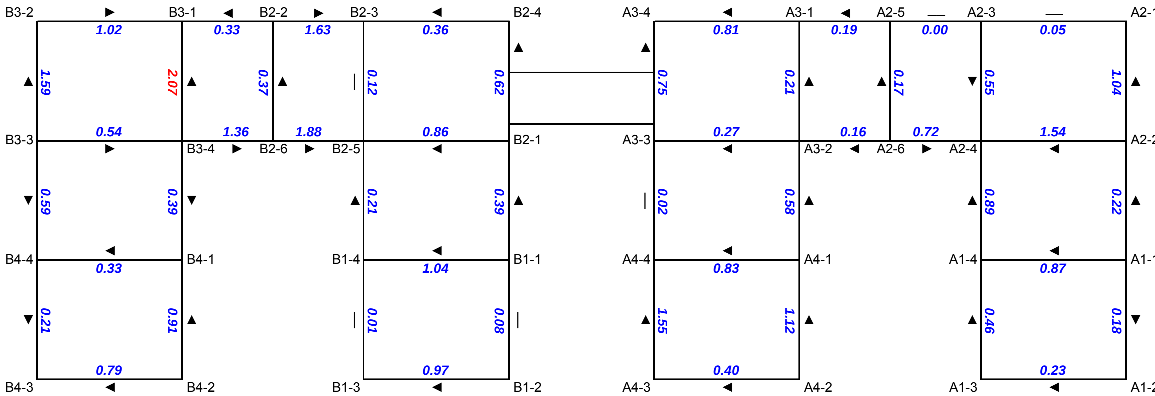

Figure 13. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2006 following recommended shimming (Table 3). (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level. Values in red indicate column pairs that exceed design limits for differential elevation.)

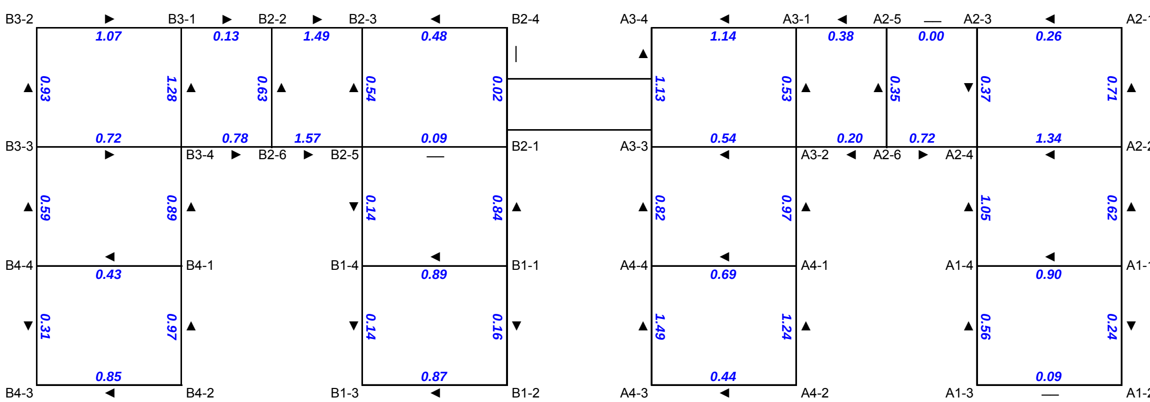

Figure 14. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2007 following recommended shimming (Table 3). (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level.)

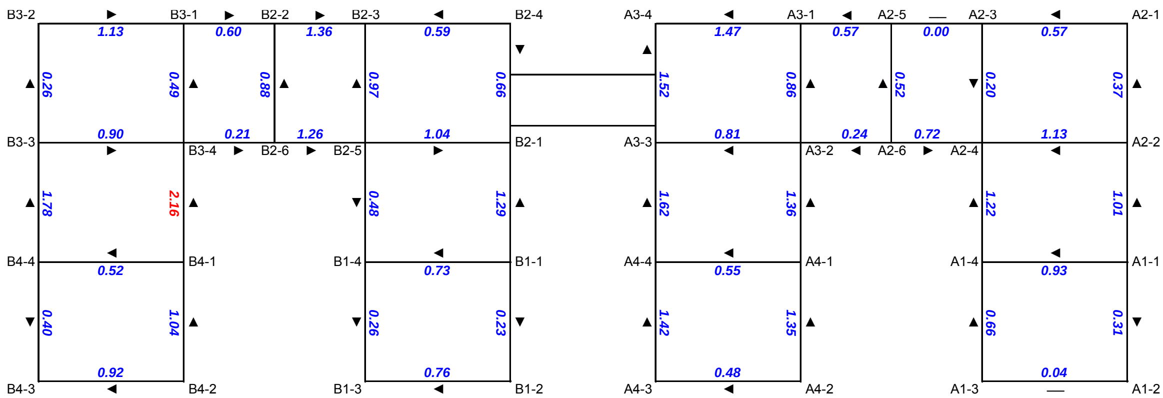

Figure 15. Predicted elevation differences (in inches) between adjacent support columns of the Elevated Station on 1 January 2008 following recommended shimming (Table 3). (Arrows indicate downslope direction of grade beam. If a dash is present instead of an arrow, the grade beam is at or very near level. Values in red indicate column pairs that exceed design limits for differential elevation.)

7 RISING TERRAIN

In addition to load-instigated settlement, all surface structures at South Pole lose freeboard continually because of snow accumulation (8 in., or 200 mm, per year). Long-term survey data for the South Pole skiway (Fig. 16), which by its nature as a runway is more isolated from surface projections than most facilities at South Pole, confirm this value (linear regression for these data yields an average slope of exactly 8 in., or 200 mm per year). Around the station, the rate is likely to be greater because of drifting associated with the concentrated plethora of infrastructure and human-introduced obstacles. However, operations management at the station is becoming more adept at limiting excess drift accumulation, and drifting will be less likely as construction is completed and the ubiquitous construction materials, equipment, and fences are removed from the immediate vicinity of the Elevated Station (Fig. 1 and 17).

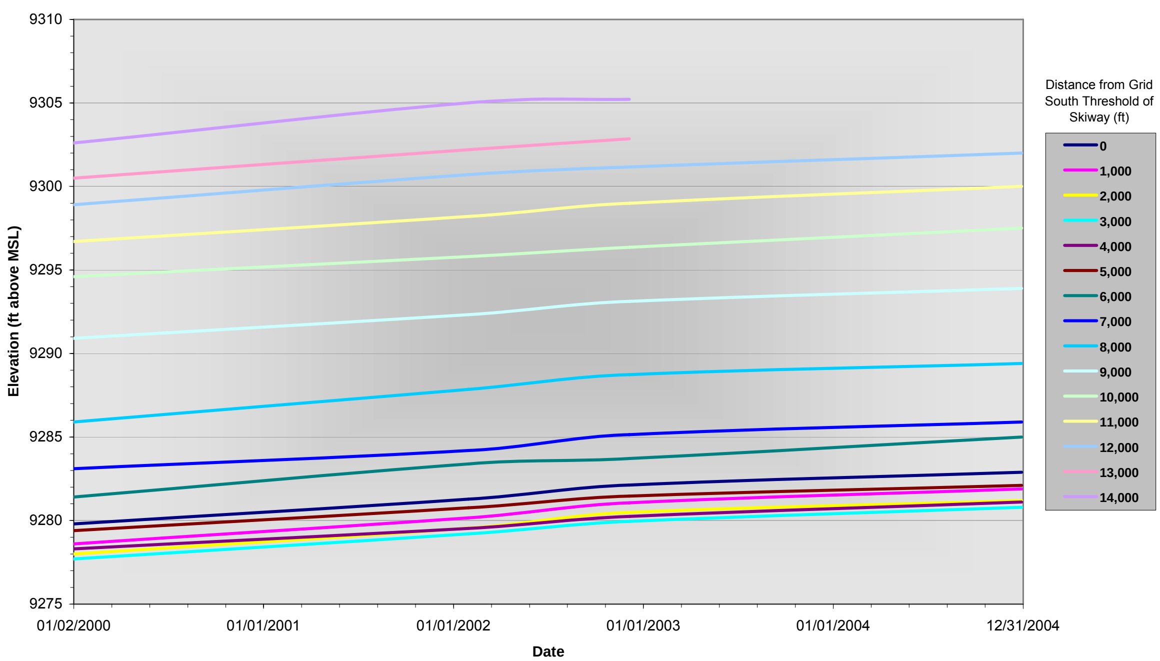

Figure 16. History of South Pole skiway elevation for 1000-ft stations along its centerline.

Figure 17. Downwind view of the Elevated Station showing the clutter associated with construction activities. This photo was taken on 24 January 2005. Note that, compared to Figure 7, the snow ramp has been removed and the superstructure of Wing's A4 and B4 are in place. The view is along the 0° meridian (true north).

8 COMPARISON WITH THEORY

During the first several years of the Elevated Station settlement monitoring, simple prediction methods (as discussed above) were necessary because (a) the data collected did not yet clearly reflect previously reported settlement behavior and (b) too little time had elapsed to reveal the potential curvilinear shape of traditional long-term settlement models. Additionally, because construction and loading were progressing slowly by comparison to classical settlement experiments, there was no assurance that the settlement curves would match those in the literature for some considerable time into the future. Nonetheless, there are compelling construction and long-term management and planning reasons to make more accurate predictions of future settlement for the station as a whole and for individual columns, to at least a 2-in. (50-mm) level of accuracy.

Several studies have derived relationships for describing the long-term settlement of static loads on deep snow. For the case of the Elevated Station, we selected from the literature the only relationship that included the entire settlement form (Shapiro et al. 1997). This is sometimes called Burger's model:

$$\varepsilon = \sigma_0 \left\{ \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2} \left[1 - \exp\left(\frac{-E_2 t}{\eta_2} \right) \right] \right\} \tag{1}$$

where ε = strain

σ_0 = stress

t = time

E_1 = Young's modulus in the purely elastic region

E_2 = effective Young's modulus for the region of elastic and pre-creep strain

η_1 = viscosity in the region of creep (permanent) strain

η_2 = viscosity in the pre-creep (semi-permanent, recoverable) region of strain.

Using the known conditions of the Elevated Station, including, where appropriate, subset(s) of the column settlement data, this relationship was developed. We assumed strain to take place within a pressure bulb developed under the timber footings. A number of field and laboratory results in mid- to high-density snow (> 0.4 g/cm^3) show that, within a pressure bulb, load concentrations diminish rapidly with depth (and are remarkably confined laterally). Abele (1990, his

Fig. 45) shows that overpressure due to a distributed surface load is less than about 30% of the value at the surface once a depth is reached equal to the width of the surface load. In the context of the Elevated Station, this depth will vary slightly since the timber footing width varies (to obtain a relatively uniform bearing pressure). We used the average width value of 12 ft (3.7 m). This is considerably less depth than the nearly 100 ft (30 m) the designers used in their analysis and can be justified by two factors. First, little overpressure due to infrastructure loading exists below 100 ft (30 m), as explained above. Second, the data we are using are referenced to a benchmark that is approximately 9 m (30 ft) below the existing snow surface. Any settlement occurring in the snow deeper than the benchmark will not be detected by our data. Thus, we postulate that settlements attributable to the Elevated Station load, occurring at depths greater than 30 ft (9 m) below the footings, are likely very small and slow. (Additionally, they are probably quite uniform laterally and thus not contributors to differential settlement.)

Stress σ_0 in eq 1 was taken as the design value of 6.9 lb/in^2 (490 g/cm^2, or 1000 lb/ft^2) (Berry and Braun 1999). Using calculations for the portion of the settlement-time curve we have measured, and using visual curve fitting, the values of modulus and viscosity were developed for the A1 and A2, the A3, and the B2 families of columns (Table 4). The results are shown in Figures 18–20.

It is clear from the data collected so far that most of the Elevated Station's wings have moved past the "elastic" stage of settlement and are at least into the "semi-permanent" stage (Fig. 4 and 6). However, the transition from elastic to semi-permanent is very subtle and can only be known with certainty when the data collected clearly show a persistent straight-line behavior (Fig. 6). This can not yet be shown with our data, meaning that curve-fitting for eq 1 can at best

Table 4. Engineering values for eq 1 derived from Elevated Station settlement results.

	A1 and A2 Wings	B2 Wing	A3 Wing
σ_0 (lb/in.^{2})	6.9	6.9	6.9
E_1 (lb/in.^{2})	200,000	200,000	200,000
E_2 (lb/in.^{2})	130	80	175
η_1 (lb-day/in.^{2})	143,415	143,415	143,415
H_2 (lb-day/in.^{2})	67,500	75,000	85,000
Zone of Influence (in.)	144	144	144

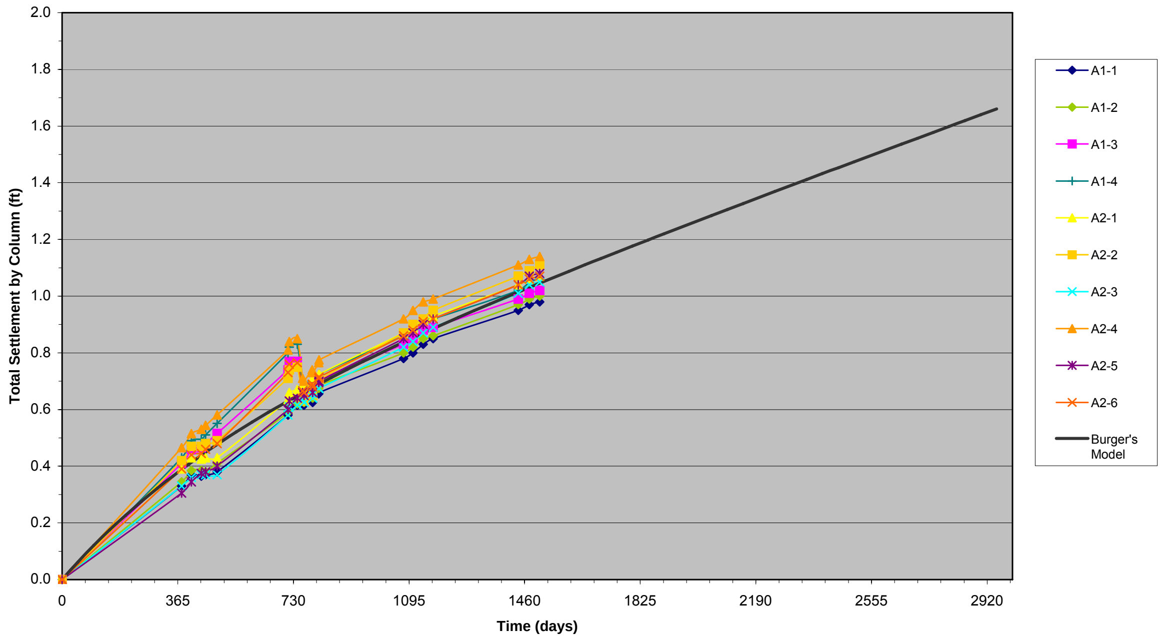

Figure 18. Curve fit of Burger's model settlement relationship to measured elevation history for Wings A1 and A2.

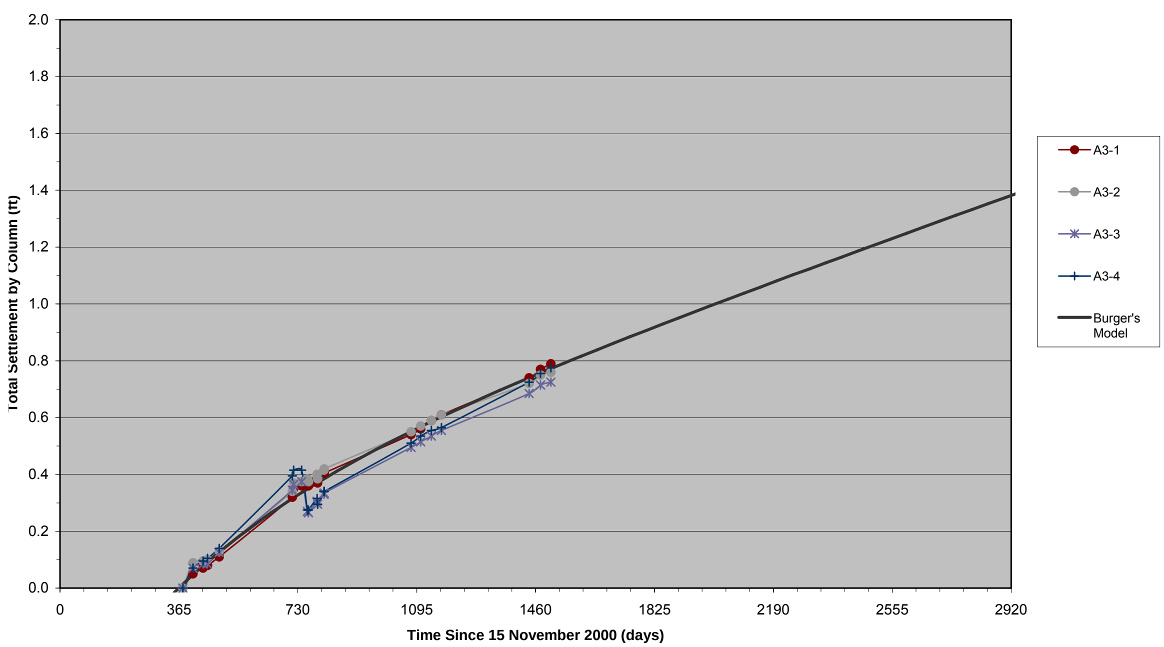

Figure 19. Curve fit of Burger's model settlement relationship to measured elevation history for Wing A3.

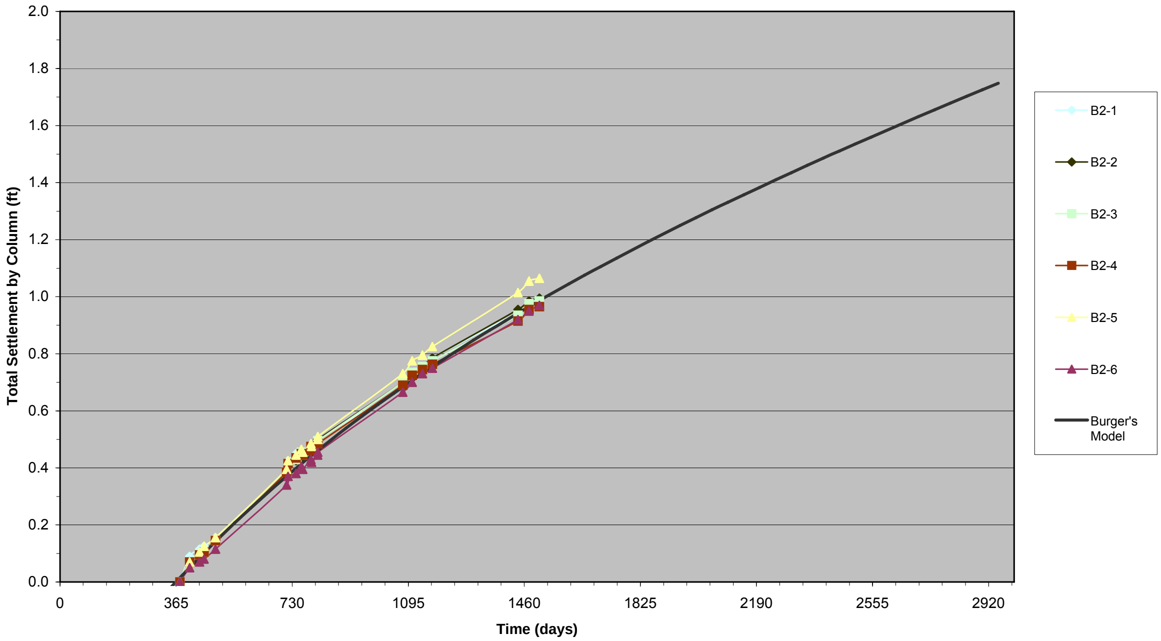

Figure 20. Curve fit of Burger's model settlement relationship to measured elevation history for Wing B2.

assume that the transition into the creep stage of settlement occurs at the time of the most recent survey. This is what we have done. Thus, the use of eq 1 with the Table 4 coefficients may well still yield conservative predictions (by overestimating settlement rates).

For this reason, we don't see any merit in fitting eq 1 to each column's settlement data and making lifting and shimming predictions. Until a longer survey history is in hand, we believe that using linear extrapolation of the prior 12 month's survey information is just as accurate. It is certainly simpler.

9 PREDICTION OF STATION JACKING INTERVAL

Elevated Station designers targeted 12 ft (3.7 m) of "sinkage" (the combination of settlement and rising terrain) as the point at which the entire facility would require jacking and insertion of column extensions (Berry and Braun 1999). Two jacking events were anticipated. Design-stage modeling predicted that 15 years would pass before this point would be reached (Brooks 1999). It is arguable when the clock should start counting the 15 years.

Prior discussion (Table 1) has established that the settlement rate of the Elevated Station is currently about 2.5 in./yr (65 mm/yr) and is expected to slow somewhat with time. For the purposes of predicting when the station will require overall jacking and column extension to increase its service life, rising terrain is clearly dominant. Total loss of freeboard should be considered to be about 10 in./yr (260 mm/yr) in 2005, slowing to perhaps 8.5 in./yr (220 mm/yr) by 2010 and beyond. An important caveat in this statement is that effective snow management techniques *must be practiced rigorously* to ensure that localized snow drifting is minimized, in keeping with the station's design.

At this time, (a) the entire support structure of the station is complete and in place on the snow, and (b) there is no evidence of the 6-ft- (1.8-m-) tall snow pad on which the station was constructed (since the pad's construction, the terrain in the immediate region of the Elevated Station has risen to the level of its top). It can then be realistically considered that, as of January 2005, the entire station's foundation was at grade on the natural local snow surface. Thus, we elected to use January 2005 as time zero.

Figure 21 shows the overall loss of freeboard for the station. The curve shown assumes that snow management is smart and effective, keeping rising terrain at a fixed rate of 8 in./yr (200 mm/yr). From this we predict that the criteria for jacking will be met in 2020, 15 years from time zero, exactly the interval anticipated by the designers! We expect that the second jacking will be required 15 or 16 years later, in 2035 or 2036. That would bring the station to the age of about 30. It is conceivable that another incremental lift could be considered; however, after 30 years, other aspects of the Elevated Station may be obsolete or requiring major rehabilitation.

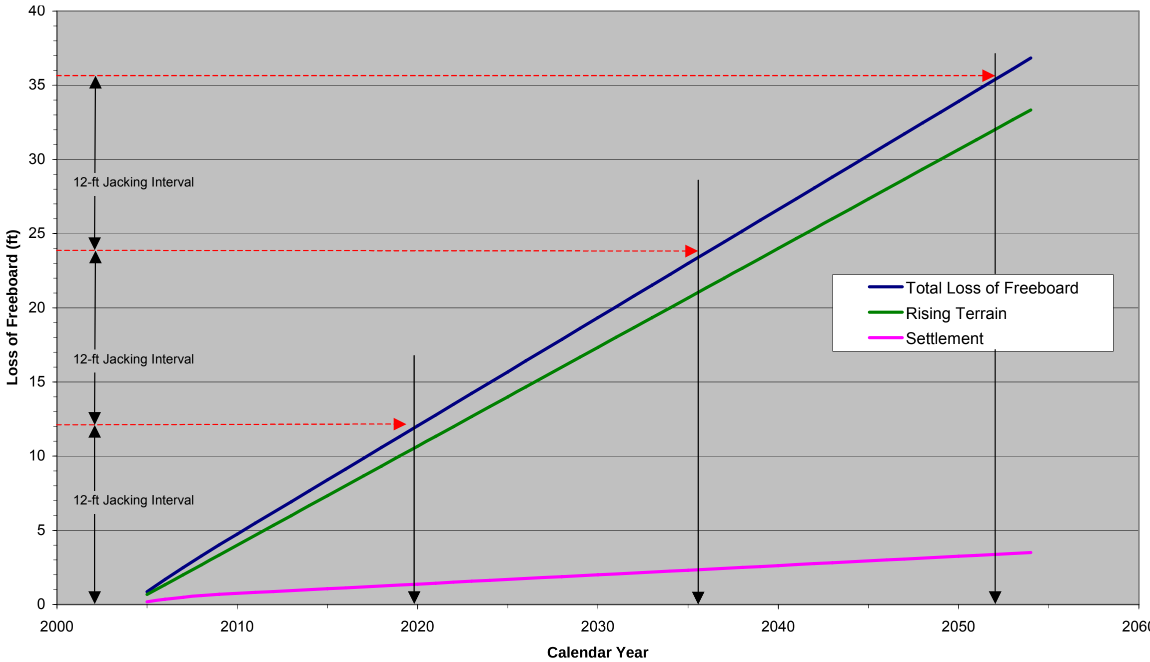

Figure 21. Predicted future loss of freeboard of the Elevated Station as a combined function of long-term settlement and the persistently rising terrain associated with this accumulation zone.

10 CONCLUSIONS

At the South Pole there are three contributors to the “apparent settlement” of the Elevated Station into the “natural” snow surface: snow accumulation or “rising terrain” (8 in./yr; 200 mm/yr), load-induced sinkage (currently 2.5 in./yr; 60 mm/yr), and snow drifting (variable based on snow management efficacy).

The design of the new Elevated Station at South Pole provided two mechanisms to accommodate total and differential settlement over time. Total settlement will be handled through a system whereby the columns are jacked and inserts placed every 15 years. Differential settlement, on the order of 2 in. (50 mm) maximum, between adjacent columns will be handled with shims at the top of each column to complete a process called station leveling.

Survey measurements of the columns support the argument that a majority of the initial differential settlement concerns were associated with the snow ramps used during construction. The ramps applied a surcharge to the compacted pad nearly 100 times greater than the design value used for the self-weight of the Elevated Station applied through the timber footers.

As Elevated Station wings are fully loaded, our findings indicate that the “raft foundation” design of the grade beams is adequate to require a limited frequency of leveling and shimming at the top of individual columns in order to manage differential settlement.

The relatively short intervals between surveys during the summer seasons illustrated a random pattern of column settlement behavior. It appears that some columns settle faster relative to others and then significantly slow down, while adjacent columns subsequently settle at faster rates. Upon elimination of any gross survey errors in data collection, we attribute this behavior to the (intended) load sharing design of the station’s rigidly connected grade beams.

The short-term pulsing of individual grade beams noted above explains the initial differential settlement experienced by the station as loads shift from columns located over weaker snow to those located over stronger snow. For short-term shimming recommendations, we used linear-fit and non-linear polynomial equations derived from existing survey data to predict column leveling performed in the 2004–2005 field season. We also used these models to predict leveling requirements for January 2006, January 2007, and January 2008.

After predicting short-term differential settlement, we attempted to define the long-term settlement of the station using Burger’s model. Our analysis indicates that the model provides an excellent fit to the long-term survey data collected on

the A1, A2, A3, and B2 Wings but will require annual adjustment until it can be certain that the station's snow foundation has entered a steady-state, long-term creep mode of load reaction.

Finally, we used the existing settlement and snow accumulation data to predict jacking intervals for the Elevated Station. Provided a successful snow management plan is implemented at the South Pole, and assuming that the long-term settlement rate of the Elevated Station slows to approximately 2 in./yr (50 mm/yr) and rising terrain remains at 8 in./yr (200 mm/yr), we determined the total loss of freeboard to be approximately 10 in./yr (250 mm/yr). Using 1 January 2005 as a starting point [since there is now no evidence of the 6-ft- (1.8-m-) tall compacted pad upon which the station was built] and using the freeboard loss estimation above, we estimate that the designers' target of jacking when the station reaches 12 ft (3.7 m) of apparent sinkage will be reached in 2020. This is exactly the 15-yr interval predicted by the station designers. An additional jacking (in 2035 after another 15 years) could potentially extend the lifespan of the Elevated Station beyond 30 years.

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14. ABSTRACT
The U.S. Antarctic Program is nearing completion of a nine-year project to reconstruct its primary facility at the South Pole. The new building is elevated and jackable to accommodate bulk and differential settlement into the snowpack. The building's foundation consists of rigidly connected grade beams from which 36 columns extend upward 13 ft (4 m) to support the state-of-the-art living and scientific facility. A limit of 2 in. (50 mm) was established as the maximum allowable elevation difference between adjacent columns to avoid structural damage to the interior of the building. Routine maintenance is required to level and shim columns when settlement limits are near. This report analyzes settlement data for the facility from November 2000 until January 2005. Settlement data so far match the pattern shown in the literature for laboratory tests of static loads on snow. Extrapolation from the most recent 12 months of survey data was used to predict the future elevations of each column for the next several years, leading to recommendations for leveling activities for the coming field season. Predictions of long-term jacking requirements based on the South Pole data match the original design estimates for the theoretical life span of 45 years.

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